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Low lying resonances in the unbound nuclei ^{11}N and ^{15}F have been calculated taking account of proton-core vibration couplings. For the extra-proton we have used an usual Woods-Saxon potential plus a surface interaction for the coupling which is deduced from the spectra of the mirror nuclei ^{11}Be and ^{15}C. Calculations for ^{11}N are in good agreement with experimental results and predict in ^{15}F two $1/2^+$ and $5/2^+$ narrow resonances at 1.2 and 2.35 MeV respectively.

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Experimental spectroscopic informations on the unbound ^{11}N, mirror nucleus of ^{11}Be, have been determined by different methods. The first data were obtained in the transfer reaction ^{14}N(^{3}He, ^{6}He)^{11}N by Benenson et al [1]. A broad resonant state at 2.24 MeV above the $^{11}N \rightarrow {}^{10}C$ +p threshold was observed. Guimaraes et al. [2] have repeated this experiment and deduced, through indirect arguments, that this broad resonance could result from two different states in ^{11}N. It was not clear to separate these two resonances, interpreted as $1/2^+$ and $1/2^-$ states in analogy with ^{11}Be. Informations have also been deduced by Thoennenssen et al. [3] from the ^{11}N->^{10}C+p decay using the stripping reaction ^{9}Be(^{12}N,^{11}N). The proton energy spectrum exhibits a broad peak at low energy, indicating that proton decays occur from at least two levels of ^{11}N. Guided by the mirror nuclei systematic, energies and widths of these two $1/2^+$ and $1/2^-$ states were roughly deduced. Recently, more direct and conclusive informations have been

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obtained by Axelsson et al [4] using the resonant scattering reaction p(^{10}C, ^{11}N) where three states below 4 MeV have been clearly identified to be $1/2^+$ (g.s.), $1/2^-$ and $5/2^+$ states. The energies of these unbound states relative to the ^{10}C+p threshold are 1.3±0.04, 2.04±0.04 and 3.72±0.04 MeV with respective width of $900^{+100}_{-200}, 690^{+50}_{-100}, 600^{+100}_{-40}$ keV. Three resonances ($3/2^-$, $3/2^+$ and $5/2^+$) have been tentatively assigned at higher energies of 4.32, 5.1 and 5.5 MeV respectively. The $3/2^-$ state surprisingly features a sharp resonance with a width of 70 keV.

These results show a great similitude with the ^{11}Be spectrum: one observes the same parity inversion between $1/2^+$ and $1/2^-$ states and close relative energies between the observed levels. It is therefore interesting to see if a same theoretical approach can explain both nuclei. Simultaneous description of these two mirror nuclei has already been considered by other authors [4,5] with Woods-Saxon potentials fitted on each $1/2^+$, $1/2^-$ and $5/2^+$ state in ^{11}Be or ^{11}N and used to study the corresponding states in the mirror nucleus ^{11}N or ^{11}Be. It is clear from their results that such correspondence exists but it is difficult to obtain a very good agreement for both nuclei even by changing the depth and the radius of the W-S potential .

The present paper proposes a somewhat different approach of the problem based on the suggestion that deviation from a Hartree-Fock or Woods-Saxon one-particle spectrum in ^{11}Be is due to strong correlations between the extra-neutron and the core of ^{10}Be [6-10]. In refs [9, 10] a deformed W-S potential is used for the neutron-core interaction, the core being described in a rotational model. In this model, the inversion is obtained only because the $1/2^-$ state is strongly pushed up by the use of an anormally strong spin-orbit potential [10], different from what is used in ^{13}C where the inversion does not appear. Conversely, in ref [8] the core is assumed to be spherical. The excited states are interpreted as vibrational states and two-body correlations are introduced as couplings between the neutron and the core-vibrations. The core of ^{10}Be has a low energy 2^+ excited state at 3.37 MeV with a very large B(E2$\downarrow$) of 10.5 ± 1.1 e^2fm^4 which is responsible for the strong effect of particle-vibration couplings on neutron energies in ^{11}Be and responsible for the inversion. In normal nuclei like ^{13}C and ^{15}C, these couplings are smaller and the inversion does not appear [8]. In this microscopic approach, a surface term depending on the neutron state (energy, angular momentum,...) is added to the

Hartree-Fock or phenomenological Woods Saxon potential. Guided by the theoretical results of ref [8] and following ref [11], we write the one body potential for a neutron in state ν as:

$$V_\nu(r) = V_{WS}(r) + 16a^2\alpha_\nu\left(\frac{df(r)}{dr}\right)^2 \quad (1)$$

where V_{WS} is the conventional Woods-Saxon potential and α_ν is the strength of the surface term adjusted in ref [11] in order to obtain the experimental energies of the $2s_{1/2}$, $1p_{1/2}$ and $1d_{5/2}$ neutron states in ^{11}Be. The Woods-Saxon potential of ref [11] is :

$$\begin{aligned} V_{WS}(r) &= V_0\left[1 - 0.44r_0^2(\vec{l}.\vec{s})\frac{1}{r}\frac{d}{dr}\right]f(r) \\ f(r) &= \left[1 + \exp\left(\frac{r-R}{a}\right)\right]^{-1} \end{aligned} \quad (2)$$

$$\text{with} \quad V_0 = -\left(50.5 + 32\,\tau_Z\frac{N-Z}{A}\right)MeV$$

$$R = r_0A^{1/3}, \quad r_0 = 1.27\,fm, \quad a = 0.75\,fm$$

A, N and Z being respectively the mass, neutron and proton number of the core nucleus ^{10}Be. τ_Z is the third component of isospin of the nucleon (τ_Z=-1 for a neutron, +1 for a proton). The resolution of Shrödinger equations with this WS potential and the surface coupling strength α_ν gives calculated energies ε_ν^{cal} that are compared to experimental ones ε_ν^{exp} in Table 1.

^{11}N is the mirror nucleus of ^{11}Be, and can be viewed as a proton outside a ^{10}C core. The corresponding Woods-Saxon potential for the extra-proton in ^{11}N is the same as for the extra neutron in ^{11}Be (the asymmetry term is identical since both (N-Z) and τ_Z change sign). The corrective term due to proton-core coupling is also expected to be the same. Indeed, ^{10}C has a 2^+ state at 3.35 MeV excitation energy with a B(E2$\downarrow$) of 12.6 ± 2.1 e^2 fm^4. As these values are very close to those of ^{10}Be, the nuclear potential $V_\nu(r)$ of eq. (1) is expected to be the same for neutron states in ^{11}Be and for proton states in ^{11}N. Therefore proton states of ^{11}N are calculated using the Woods-Saxon potential of eq (2), the coupling strengths α_ν of table 1 and the Coulomb potential of a uniformly charged sphere with the same radius r_o. Since these states are unbound, calculations have been made in two different ways :

1- The continuum states are calculated as discrete states of energies ε_b by requiring that the radial wave function vanishes at a distance of 20 fm.

2- The Schrödinger equation is solved for positive proton energies ε. We know that the resonance wave function is concentrated in the interior of the potential. Therefore, to determine the resonance , we calculate the function $I_v(\varepsilon)$ defined as:

$$I_V(\varepsilon) = \int_0^{R_0} |\varphi_V(r,\varepsilon)|^2 r^2 dr$$

where φ_v is the wave function of the proton at energy ε and R_o=5 fm. We have checked that the position and width of the resonance are independent of the adopted value R_o between 3 and 6 fm. The resonance energy ε_r is determined at the maximum of the function $I_v(\varepsilon)$, whereas the width of $I_v(\varepsilon)$ at half maximum is associated with the width of the resonance (the correspondence is true for a square well potential [12]).

Fig. 1 shows the function $I_v(\varepsilon)$ for the $2s_{1/2}$, $1p_{1/2}$ and $1d_{5/2}$ resonances. Table 2 gives the energies ε_b and ε_r calculated with the first and the second method and the widths calculated from method 2. They are compared with the experimental resonance energies ε_{exp} and widths Γ_{exp}. The nearly perfect agreement found between the two calculated energies ε_b and ε_r is a good test of the first method used in many calculations. Very good agreement is also found between calculated and measured energies. The agreement is improved compared with previous calculations [4,5]. This shows that the one-body potential of eq (1) is more successful than a pure Woods-Saxon potential to describe simultaneously ^{11}Be and ^{11}N and emphasizes the role of surface couplings to describe halo phenomena. The calculations of the widths Γ overestimate the experimental values. As seen in Fig. 1, the functions $I_v(\varepsilon)$ are very asymmetric with a long high-energy tail, especially for the $1/2^+$ state, and the width of $I_v(\varepsilon)$ at half-maximum gives qualitative information only. On the other hand we know that these states are not pure and a mixture of configurations would decrease the calculated widths [5]. However the agreement is qualitatively satisfactory : the s resonance is broader and the p and d resonances exhibit similar widths.

In the most recent experiment [4], apart from the three lowest well-determined resonances, some structures in the proton excitation function are also seen in the vicinity of 4.5

MeV above the ^{10}C+p threshold. The analysis of excitation function suggests the presence of a very narrow $3/2^-$ state at 4.35 MeV (with an excitation energy of 3.15 MeV) with a very small width Γ = 70 keV which could be the analog of the known narrow $3/2^-$ level in ^{11}Be at 3.9 MeV excitation energy with Γ = 15 keV. A plausible description of such $3/2^-$ states corresponds to two neutrons (protons) coupled to 0^+ and forming the ground state of ^{12}Be (^{12}O) plus a neutron (proton) hole in the $1p_{3/2}$ shell [4]. Neglecting the coupling between the two particles and the hole, the $3/2^-$ state energies in ^{11}Be and ^{11}N can be calculated as:

$$\varepsilon(3/2^-) = S_n(^{10}Be) - S_{2n}(^{12}Be) \qquad \text{for } ^{11}Be$$

$$\varepsilon(3/2^-) = S_p(^{10}C) - S_{2p}(^{12}O) \qquad \text{for } ^{11}N \qquad (3)$$

where S_{2n} (S_{2p}) and S_n (S_p) are the two-neutron (two-proton) and one-neutron (one-proton) separation energies respectively. Using the separation energies of ref [12] in eq (3) we get 3.6 MeV and 4.6 MeV for the excitation energies of the $3/2^-$ states in ^{11}Be and ^{11}N respectively.
In ^{11}Be the agreement is quite good while the $3/2^-$ state in ^{11}N is too high compared to the experimental one of 3.15 MeV [4]. In our uncorrelated model, the width is given by the widths of the two-particle states. As ^{12}Be is bound, the width in ^{11}Be is due to the coupling with other configurations only and should be small as it is found experimentally. The situation is different in ^{11}N since the ^{12}O ground state is unbound with a width Γ = 400-450 keV. Therefore the $3/2^-$ level should have a width of about 450 keV, much larger than the measured one. Within this simple model, the properties of the $3/2^-$ states in ^{11}Be and ^{11}N cannot be simultaneously reproduced.

Another interesting unbound nucleus is ^{15}F which is the mirror of ^{15}C . No spectroscopic study of ^{15}F have been investigated so far but, in a one nucleon+core model, the correspondence between ^{15}F (p+^{14}O) and ^{15}C (n+^{14}C) is the same than between ^{11}N and ^{11}Be. We then expect the ground state of ^{15}F to be a $1/2^+$ state as in ^{15}C corresponding to a proton in a $2s_{1/2}$ state. We have performed the same calculation for ^{15}F as for ^{11}N. We use the same potential of eq. (1) where the Woods-Saxon potential is the same as previously and where the parameters α_v are fitted in order to reproduce the $2s_{1/2}$ and $1d_{5/2}$ neutron states in ^{15}C. Indeed the level spectra of the core nuclei ^{14}C and ^{14}O are very similar. Thus, the correction to the Woods-Saxon potential due to particle-core vibration couplings for a neutron state in ^{15}C (neutron + ^{14}C core) and a proton state in ^{15}F (proton + ^{14}O core) is expected to be similar and small [8]. The calculated and experimental energies of the $1/2^+$ and $5/2^+$ states in ^{15}C are given in Table 3. They correspond to $\alpha_v = -1.55$ MeV for the $2s_{1/2}$ neutron-state and to $\alpha_v=0$ for the $1d_{5/2}$ neutron-state. With this potential we have calculated the unbound $1/2^+$ and $5/2^+$ states in ^{15}F which are given in Table 4 and Fig. 2. We predict the $1/2^+$ ground state of ^{15}F at an energy of 1.2 MeV above the $^{14}0$+p threshold with a width Γ = 500 keV and a $5/2^+$ excited state at 2.35 MeV above the threshold with a narrow width Γ = 150-200 keV.

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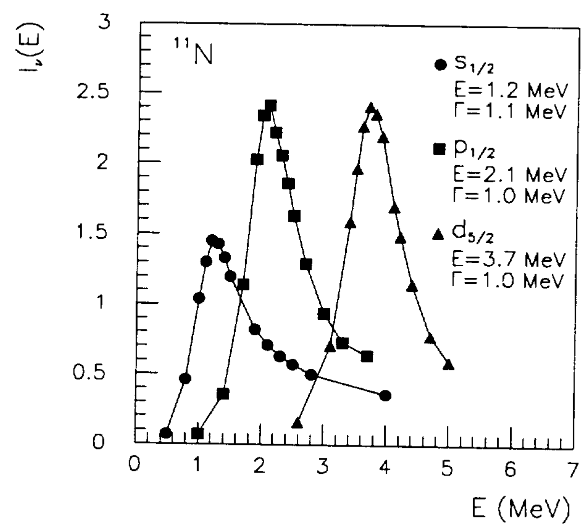
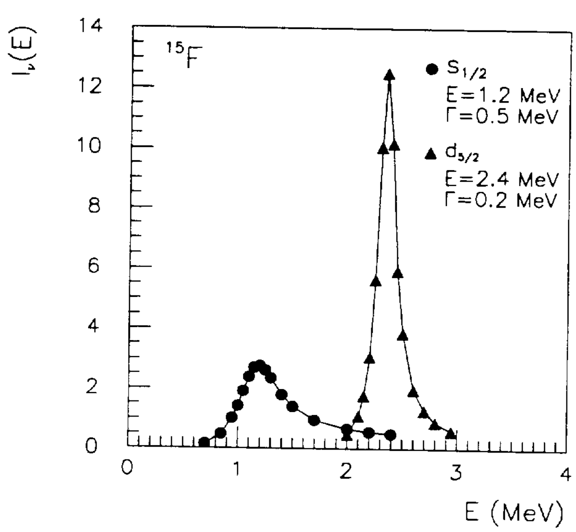
<u>Figure captions</u>

Fig. 1 : Functions $I_\nu(E)$ for the $2s_{1/2}$, $1p_{1/2}$ and $1d_{5/2}$ resonances in ^{11}N. E is the energy above the $p+^{10}C$ threshold.

Fig. 2 : Functions $I_\nu(E)$ for the $2s_{1/2}$ and $1d_{5/2}$ resonances in ^{15}F. E is the energy above the $p+^{14}O$ threshold.





Tables:

Table 1: α_ν strengths and neutron energies in ^{11}Be

states ν of ^{11}Be	α_ν [MeV]	ε_ν^{cal} [MeV]	ε_ν^{exp} [MeV]
$1p_{1/2}$	5.45	-0.21	-0.18
$2s_{1/2}$	-10.56	-0.53	-0.5
$1d_{5/2}$	-4.0	1.29	1.27

Table 2: Calculated proton resonance energies ε_b, ε_r and widths Γ_r in ^{11}N compared to experimental values ε_{exp} and Γ_{exp}. Values of energies are relative to the the p+^{10}C threshold.

^{11}N states	ε_b [MeV]	ε_r [MeV]	ε_{exp} [MeV]	Γ_r [MeV]	Γ_{exp} [keV]
$s_{1/2}$	1.29	1.2	1.3 ± 0.04	1.1	990^{+100}_{-200}
$p_{1/2}$	2.17	2.1	2.04 ± 0.04	1	690^{+50}_{-100}
$d_{5/2}$	3.9	3.7	3.72 ± 0.04	1	600^{+100}_{-40}

Table 3: α_ν strengths and neutron energies in ^{15}C

states ν of ^{15}C	α_ν [MeV]	ε_ν^{cal} [MeV]	ε_ν^{exp} [MeV]
$2s_{1/2}$	-1.55	-1.25	-1.21
$1d_{5/2}$	0	-0.73	-0.5

Table 4: Predicted proton resonance energies and widths in ^{15}F. Values of energies are relative to the the p+^{14}O threshold.

^{15}F states	ε_r [MeV]	Γ_r [MeV]
$s_{1/2}$	1.2	0.5
$d_{5/2}$	2.35	0.15